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Investigation of surface integrity in high speed milling of gamma titanium aluminide under dry and minimum quantity lubricant conditions

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Abstract

Intermetallic alloys based on gamma titanium aluminide are considered to be one of the replacements for nickel-based superalloys. The machinability of γ-TiAl is faced with restrictions due to the alloy's mechanical and metallurgical properties. Machining of γ-TiAl causes defects such as micro cracks. In this study surface integrity of High Speed Milling of γ-TiAl was examined under dry and Minimum Quantity Lubrication condition. Minimum Quantity Lubrication as a sustainable lubrication method in machining processes, improved energy consumption, environmental impact, personal health, while enhancing the machining affected zone properties in comparison with floating method. Three dimensional surface topography and other effects of surface alterations, including deformations of the lamellae and micro cracks were studied. Microhardness evaluation of the surface and subsurface indicated a significant difference between them.

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Keywords: Microhardness, Surface integrity, High Speed Machining, Gamma titanium aluminide, Minimum quantity lubrication.

1. Introduction

Experiments on lightweight materials are usually performed under high operational temperatures. Lightweight materials are used in components such as gas turbine engines and automotives. Generally, to increase the efficiency of gas turbine engines, the weight should be reduced and the operating temperatures should be increased. These conditions require the use of lightweight and high-temperature materials, particularly for rotating and reciprocating components such as turbochargers, exhaust valves and turbine blades [1]. Intermetallic alloys based on gamma titanium aluminide (γ-TiAl) offers a combination of low density, high-temperature stiffness, high-temperature yield strength, creep resistance and wear resistance. Despite these positive properties, the use of γ-TiAl is limited due to poor toughness, low ductility at room temperature, high production costs [2] and difficulty in machining because of its high strength and brittleness, low thermal conductivity and high temperature properties. However, owing to the relative advantages of γ-TiAl, research is being performed to mitigate the deficiencies of this material to achieve an acceptable surface integrity [3].

2. Machining of γ-TiAl

Despite the progress in alloy design and the study of the creep and fatigue behavior of γ-TiAl, limited research has been conducted on the machining of γ-TiAl. This material is difficult to shape by conventional methods, such as machining and extrusion, because of its lack of ductility [4]. Investigation of the Machining Affected Zone (MAZ) and surface integrity can contribute to the optimization of the machining processes of γ-TiAl and modifications of its surface integrity.

The researches in the field of titanium-aluminide machining demonstrate the high chemical reactivity of titanium, high temperatures at the tool tip and low thermal conductivity of the material [5]. All of these properties contribute to excessive tool wear and tedious material removal during the machining process [6]. Machining of γ-TiAl is more difficult compared with ordinary titanium-aluminum alloys, such as Ti-6A1-4V [7]. This difference is due to the low ductility, high brittleness and low heat conductivity of γ-TiAl.

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Zhang et al. reported on the first efforts of γ-TiAl machining. The reports concluded that turning γ-TiAl with PCBN and an alumina based ceramic proved unsuitable in low cutting speeds [8]. Instead, Zhang et al. recommended straight-grade cemented carbide with a grain size less than 0.8 micron for low cutting speeds [9]. In 1999, Aust et al. indicated that by using low cutting speeds, high quality surface roughness can be obtained [10]. Bentley et al. discovered that compared with grinding, the fatigue strength of γ-TiAl intermetallic alloys increased significantly using high speed milling (HSM) [11]. Aust et al. also concluded that compressive residual stress on the surface and subsurface lamella and lamellae deformation resulted in restricting the crack growth probability in High Speed Milling (HSM) [12].

Finish turning γ-TiAl can cause surface damage such as cracked particles. Sharman et al. reported that when machining γ-TiAl, cutting speeds of more than 30 m/min, causes rapid wear of carbide tools unless the chip load is considerably reduced [13]. Aust et al. reported cutting speeds of 17-20 m/min for end milling [10]. Vargas has performed experiments using a maximum cutting speed of 400 m/min [14]. In comparison, Mantle et al. reported cutting speeds of 70-120 m/min while [15]. Experimental tests were performed by Ge et al. on dry HSM of γ-TiAl alloy with cutting speeds of 60-240 m/min to investigate the tool wear, milling forces and surface roughness [16]. J.Sun showed that increasing the cutting speed could improve surface integrity in comparison with Ti–6Al–4V [17]. However, increasing the cutting speed could increase the milling forces and decrease the tool life. The material removal process is important to avoid surface cracks and overheating the workpiece. In addition, the control of the heat generated at the tool tip is very important because it can affect the surface integrity [18].

Due to the thermo-mechanical effects that are generated near the material surface during machining, it is possible to limit the heat treatment to specific areas and to a certain depth where a transformation (hardening and phase transformation) occurs by lubrication and cooling method. The bulk of the material is not heated up to critical temperatures and therefore will not transform. Moreover, the thermal load of the whole component is minimized and thus the distortion can be avoided. Most of the researches in the field of the machining of γ-TiAl have failed to achieve the surface full free of microcracks after machining. Literature reviews of γ-TiAl machining, declare the lack of the research on the effect of the Minimum Quantity Lubrication (MQL) on surface integrity, which is needed for machining components. Therefore, in this study the effects of HSM on γ-TiAl under dry and MQL as a sustainable lubrication method was scrutinized. There were no micro cracks or surface tears on the surfaces of the machined samples in the present work.

3. Experimental procedure

The γ-TiAl sample used in the present work was as investment cast with Ti-48Al-2Cr-2Nb-1B (%at) in billet form, which was HIPped at 1250 °C, at a pressure of 150 MPa for 4 hours, in a pure Argon atmosphere and heat treated in 1380 °C for 1 hour. The nominal bulk hardness of the sample was 320 $HV_{0.015}$. The cast skin was removed, before the machining tests.

A series of HSM tests conducted on a 5-axis CNC milling machine Chiron FZ 12MT under dry conditions and MQL conditions. Tests were carried out employing a continuously variable spindle speed up to a maximum of 40000 RPM. Semi-synthetic vegetable oil was used as lubricant and was supplied to the machining zone through a nozzle at a distance of 50 millimeters from the tool tip with the rate of 50 milliliters per hour. A solid super fine micro grain tungsten carbide end mill with 12 mm in diameter (4 flutes) was used (TiAlN nanocoating). The tool selection was based on the previous studies and the recommendations of the tool manufacturing companies for titanium and super alloys machining [19-20]. Two levels of the cutting speed, two levels of axial depth of cut and two levels of coolant conditions were used. The feed rate and radial depth of cut remained constant. Full factorial method was used for the Design of Experiments (DOE). The details of the experiments are listed in Table 1. 16 tests based on full factorial design were carried out (8 tests with 2 replicates).

Table 1. Machining parameters.

Feed rate *f* (mm/per tooth rev)	Axial Depth Of Cut (mm)	Coolant condition	Cutting speed V_C (m/min)	Radial Depth Of Cut a_p (mm)
0.005	0.10 mm	Dry	300 m/min	5 mm
	0.20 mm	MQL	600 m/min	

Surface topography and roughness were measured and assessed using a stylus profiler, an optical microscope and a Scanning Electron Microscope (SEM). SEM and optical images of the subsurface microstructure after etching were taken. Each sample for metallographic preparation was mounted and ground using Al_2O_3 waterproof paper and was polished with diamond paste. Samples were then polished in two steps: (1) using a solution containing six and one micron diamond and colloidal silica solution (SiO_2) and (2) using hydrogen dioxide (H_2O_2) and ammonium hydroxide (NH_4OH). The samples were etched using Kroll's reagent (95% H_2O, 3% HNO_3 and 2% HF) for 10 to 25 seconds. Microhardness Vickers measurements of samples were recorded using a 15-50-100-200 gram load on a Shimadzu HMV-2 to ensure the accuracy of the measurement. The subsurface microstructure of the samples was analyzed using a Leitz Wetzlar optical microscope connected to a digital camera and Philips XL 30 scanning electron microscope. Surface roughness was measured using a portable Mahr perthometer M2. Surface topography were measured and assessed using a stylus profiler, an optical microscope and SEM. SEM and optical images of the subsurface microstructure after etching were taken. Fig. 1 shows the machining setup of the experiments. The subsurface microstructure of the samples was analyzed using a Leitz Wetzlar optical microscope connected to a digital camera and Philips XL 30 scanning electron microscope.

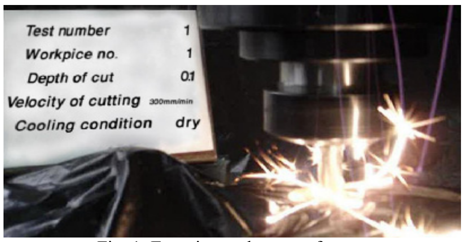

Fig. 1. Experimental set up of tests.

3.1. Surface integrity characterization

Surfaces with low surface roughness decrease the probability of micro crack formation and increase fatigue strength [21].

3.1.1. Surface roughness

Surface roughness is the most investigated characteristic of the HSM processes, mainly due to the competition between HSM and grinding. Surface roughness in machining depends on several factors, such as cutting speed, depth of cut, tool wear, feed rate, tool materials, workpiece material and chatter of machine [13]. Increasing cutting speed generally results in a decrease in surface roughness, but not for titanium-aluminum alloys. In the present work, six Ra measurements were taken for each machining sample. As depicted in Fig. 2, surface topography shows the anisotropic nature of the surface, meaning that surface roughness values differ in different directions. All measurements of Ra were taken in the direction of feed rate and cutting direction. The average measurements of the worst cases were considered in the present work. Some surface roughness values are presented in Table 2. These values indicate that cutting speed had a significant effect on determining surface roughness in all cases. Table 2 also shows that the Ra values produced in dry and MQL conditions range from 0.155 to 0.523 µm and 0.170 to 0.544 µm, respectively. Apart from Ra values, additional parameters such as Rk, Rvk and Rt, should also be considered for fatigue life [11-12].

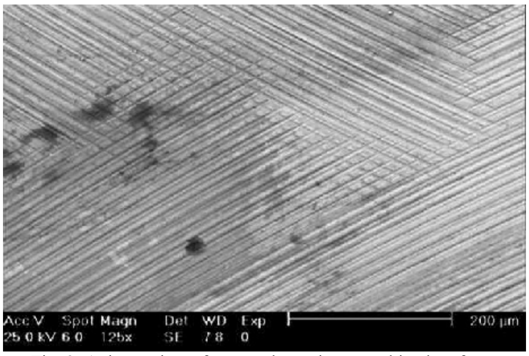

Fig. 2. Anisotropic surface roughness in as machined surface.

Table 2. Surface roughness measured in HSM and WEDM and grinding.

Sample & sequence No	Machining Parameters	Ra (µm)	Rq (µm)	Rz (µm)	Rvk (µm)
1	V_C 300 m/min, ADoC 0.1 mm, dry	0.364	0.492	1.88	0.57
2	V_C 300 m/min, ADoC 0.1mm, MQL	0.170	0.271	1.52	0.32
3	V_C 600 m/min, ADoC 0.1mm, dry	0.155	0.228	1.06	0.30
4	V_C 600 m/min, ADoC 0.1mm, MQL	0.195	0.333	1.86	0.49
5	V_C 300 m/min, ADoC 0.2mm, dry	0.523	0.908	3.20	1.72
6	V_C 300 m/min, ADoC 0.2mm, MQL	0.429	0.741	2.18	1.75
7	V_C 600 m/min, ADoC 0.2mm, dry	0.367	0.604	2.16	0.66
8	V_C 600 m/min, ADoC 0.2mm, MQL	0.544	0.755	2.41	-

It was concluded from the measurements of surface roughness that the best Ra value was obtained using a cutting speed of 600 m/min, 0.1 mm Axial Depth of Cut (ADoC) and dry conditions. ADoC and cutting speed have the most important effects on the surface roughness respectively. In addition, an analysis of variance (ANOVA) showed that by employing MQL, the surface roughness value decreases. Similar results were obtained from the investigation of Rq, Ra, Rt, Rk and Rvk. Fig. 3 shows that the surface roughness in HSM of γ-TiAl is sensitive to HSM parameter changes

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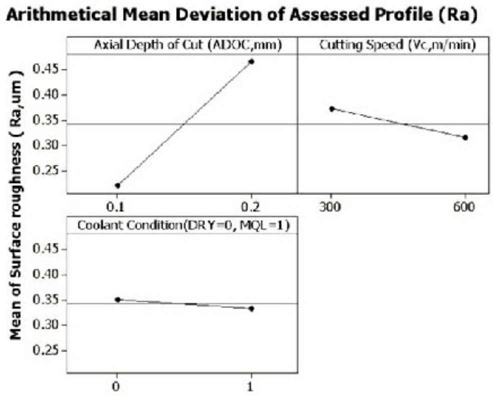

Fig. 3. A plot of different machining parameters vs. Ra by ANOVA.

Fig. 4 shows the interaction effect analysis of HSM parameters on surface roughness. Section A indicates that increasing the cutting speed results in decreasing Ra. This effect seems to be more noticeable in low ADoC. Fig. 4, section B shows the results of surface roughness in dry and MQL HSM. It can be seen that when cutting speed is 300 m/min, Ra in MQL machining is less than dry machining. However, when the cutting speed is 600 m/min the results are reversed.

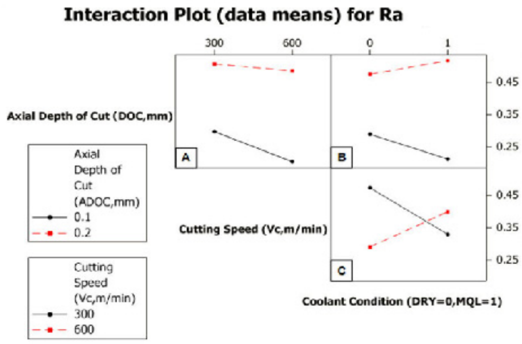

Fig. 4. Interaction plot of HSM parameter vs. Ra.

Fig. 4, section C demonstrates that by increasing the depth of cut, surface roughness deteriorates as the coolant condition changes from dry to MQL. Thus, employing MQL techniques can improve surface roughness in low ADoC. Table 3 shows a comparison of surface roughness reported by other researchers with the present work.

Table 3. Surface roughness in machining of γ -TiAl

Reference no.	Best result of Ra (µm)	Mean result of Ra (µm)
Bentley et al. - Roughing ground [11]	1.09	-
Sharman et al. – Turning [12]	0.84	-
Aust et al. [10]	0.8	1.5
Mantle et al. [22]	0.49	1
Beranoagirre et al. [23]	0.31	.45
Ge et al. [16]	0.2	0.5
Results of the present work	0.13	0.31

3.1.2. Three-dimensional surface topography

A three-dimensional image of surface topography, shown in Fig. 5, contains valuable surface data. An area measuring 80 micron (x) by 50 micron (y) of the sample's machined surface was covered as shown in Fig. 5. The measurement method of three-dimensional surface is based on a combination of digital holographic microscopy and SEM photogrammetry. Moreover, image-processing software was used for the analysis of the three-dimensional images of surface topography. Three lines (1 to 3) in the vertical direction of lay are shown in Fig. 5. The arrows shown in Fig. 5(left) mark the starting points of these lines. The two-dimensional curves of lines 1 and 2 are shown in Fig. 5(right).

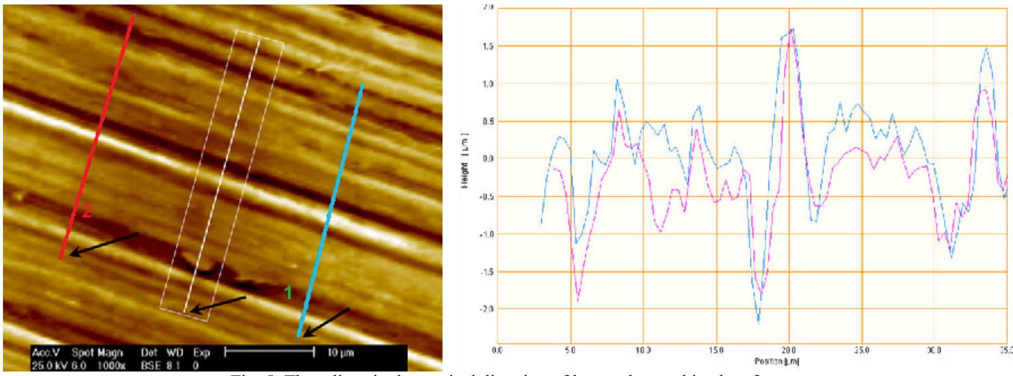

Fig. 5. Three lines in the vertical direction of lay on the machined surface.

A three-dimensional surface topographical image of this sample was shown in Fig. 6.

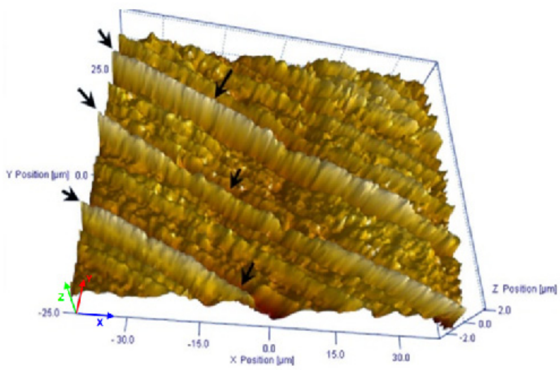

Fig. 6. Three-dimensional surface topography of the machined surface

The tip of the arrow in the Fig. 6 points to the peaks in the three-dimensional topographic surface. The three-dimensional parameters of surface roughness are based on ISO/DIS 25178-2 ASME B46.1 and are given in table 4. Sa expresses the average of the absolute values of Z(x,y) in the measured area. It is equivalent to the arithmetic mean of the measured region of the three-dimensional display diagram when valleys have been changed to the peaks by conversion to absolute values. Sq It expresses the root mean squared of Z(x,y) in the measured area. It is equivalent to the average mean squared of the measured region on the three-dimensional display diagram when valleys have been changed to high peaks by squaring [24].

Table 4. Three-dimensional surface parameters of Fig. 6.

Sa	502.318 nm
Sq	667.947 nm

3.2. SEM observation

SEM images were used to analyze the surface microstructure and chemical composition of the machined surfaces. Micro cracks or surface tears on the surfaces of the machined samples in the present work was not observed. Increase in cutting speed results in a decrease in the sharpness of peaks and valleys on the surface.

Fig. 7 shows samples no. 6. The machining parameter used in this sample is the same as the parameters used for samples no. 2 except for the ADoC. The ADoC for sample no. 6 increased to 0.2 mm.

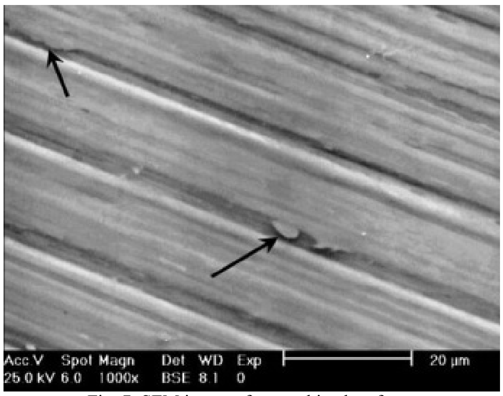

Fig. 7. SEM image of as machined surface.

Fig. 7 shows that an increase in ADoC results in chip development on the surface of the samples. These burrs are shown with an arrow in Fig. 7. Using MQL and increasing the cutting speed decreases surface roughness and changes the texture of the surface considerably. Increasing the ADoC cause to increase the amount of burrs and chips that can develop on the surface of the material. The remaining chips on the surface increase the surface roughness. It should be noted that a similar phenomenon was reported in the grinding of titanium aluminide [25-26].

3.3. Deformation of subsurface layers

The surface and subsurface microstructures of the machined samples were examined using SEM and optical microscopy. Fig. 8 shows a SEM micrograph cross section of polished and unetched samples. Cross sections of the samples were etched with Kroll's reagent in three levels (7, 10, 25 seconds). Analysis of the SEM images revealed that the machined sample surfaces are fully free of microcracks.

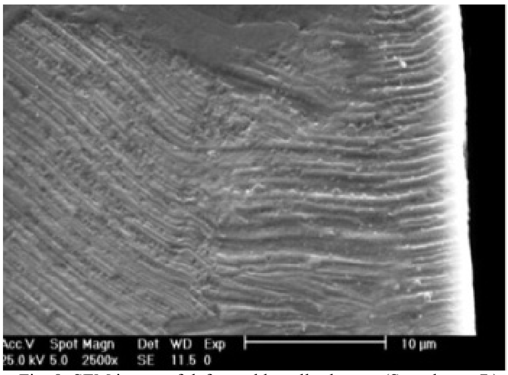

Fig. 8. SEM image of deformed lamellar layers. (Sample no. 7.)

Deformed lamellae were observed in the surface samples. Surface and subsurface layers were simultaneously deformed plastically. Different strategies exist for the measurement of subsurface Plastic Deformation Depth (PDD) such as changing the microhardness and microstructure. The PDD determination method is based on the measurement of the depth of deformation of laminated layers.

SEM was utilized to determine the depth of this layer. Five PDD measurements were done in the cross sectional area of each specimen and the average was calculated. Measurements of the subsurface plastic deformation depth showed the thickness of this layer changed and varied according to parameters of HSM significantly. Therefore, a close correlation exists between the PDD and HSM variable parameters. However, due to the high strain rate deformation and high temperature generated in HSM, Severe Plastic Deformation (SPD) transpired. The MAZ also formed with unique properties. In the samples subjected to HSM, the thickness of PDD was very small compared with the workpieces subjected to a conventional cutting condition such as turning and grinding [27-28].

Microhardness profiles for HSM assisted MQL of γ-TiAl are shown in Fig. 9. An increase in subsurface micro hardness and subsurface deformed layers resulted in a substantial increase in fatigue life. It is likely that the deformation of the microstructure in the HSM surfaces restricts crack growth from the lamellae boundaries, thereby restricting interlamellar failure and further increasing the fatigue strength of the material.

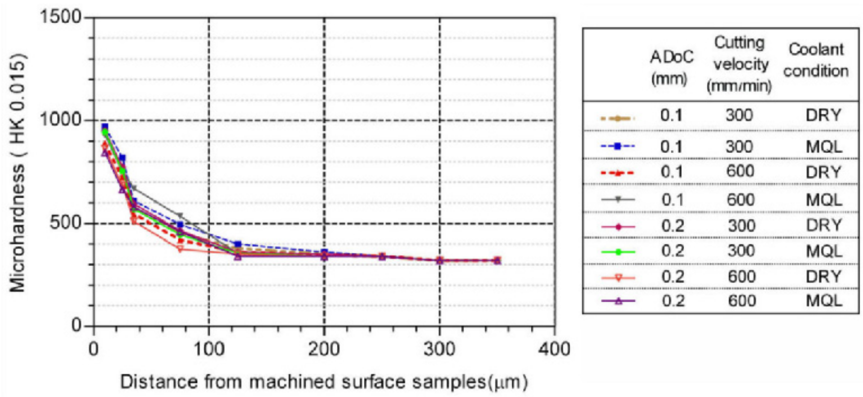

Fig. 9. Microhardness profiles for HSM of γ -TiAl dry and MQL

Discussion

Surface roughness values measured (Ra) in machined samples were in the range of 0.13 mm to 0.31 mm. A comparison between the results of surface roughness values in the present study with the results of previous researches was shown in table 3. In the present study surface roughness were improved due to the rigidity of the milling tool caused by the larger diameter tool in comparison to previous work [29-30] and increasing cutting speed in comparison other study in the field of high speed machining of gamma titanium aluminide [31-32]. The absence of plastic deformation and cracks observed in surface cavities are indicative of the low ductility of the γ-TiAl [13]. Generate high temperatures in the shear zone for the purpose of reaching the brittle to ductile transition temperature are detailed in publications by Uhlmann et al. [33]. Plastic deformation was reported in the bending form of the lamellae [29]. Bending of lamellae in as machined surface and subsurface layer was comparable to the reported result of Klocke et al. [32].

In respect of energy consumption and cost of fluid consumed, MQL is significantly lower than flood coolant due to use of reduced fluid volume and less power demand for fluid pumping operations. Energy consumption reduced 87% (from 85KJ to 11KJ per a day) and cost of fluid reduced about 63% per month in a high speed milling machine that used in this study.

Conclusion

The machinability of γ-TiAl intermetallic alloys has been evaluated and characterized through two and three dimensional scanning strategies. Surface roughness, microstructure, phase transformation and surface integrity were all examined. In HSM, a self-induced hot machining regime was generated. Heat generated techniques softened the gamma titanium aluminide in the shear zone, making it easier to cut. By using HSM, new and unique surface layers were formed. The results indicate that the properties of the surface layer of γ-TiAl were corrected in many cases. Using low depth of cut, high speed cutting and assisted MQL, a crack-free layer was formed. In this instance, cutting force and tool wear increased rapidly. The achievements of this research are the following:

1. Two and three dimensional surface parameters were studied.
2. SEM observation of surface layers shows a significant relation between machining parameters and SEM observations.
3. The maximum microhardness obtained was about 1050 $HV_{0.050}$ and the hardened layer was confined to 150 micron below the machined surface.
4. MQL as a sustainable lubrication method in machining processes, improved MAZ properties in comparison with the conventional floating method.
5. MQL decreased significantly the cost of related to fluid and energy consumption in comparison to flood coolant method.

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